Operationally Optimal Maneuver Strategy for Spacecraft Injected into Sub-Geosynchronous Transfer Orbit

B. S. Kiran, Kuldeep Negi & Satyendra Kumar Singh
Flight Dynamics Group, ISRO Satellite Center, Bangalore-560 017, India

Abstract

The GSAT-12 spacecraft is providing Communication services from the INSAT/GSAT system in the Indian region. The spacecraft carries 12 extended C-band transponders. GSAT-12 was launched by ISRO's PSLV from the Sriharikota, with a lift-off mass of 1410 kg, into a sub-geosynchronous Transfer Orbit (sub-GTO) of 284 x 21000 km with inclination 18 deg. This Mission successfully accomplished combined optimization of launch vehicle and satellite capabilities to maximize the operational life of the s/c. This paper describes mission analysis carried out for GSAT-12 comprising launch window, orbital events study and orbit raising maneuver strategies considering various Mission operational constraints. GSAT-12 is equipped with two earth sensors (ES), three gyroscopes and digital sun sensor. The launch window was generated considering mission requirement of minimum 45 minutes of ES data for calibration of gyros with Roll-sun-pointing orientation in T.O. Since the T.O. period was a rather short 6.1 hr, required pitch biases were worked out to meet the gyro-calibration requirement. A 440 N Liquid Apogee Motor (LAM) is used for orbit raising. The objective of the maneuver strategy is to achieve desired drift orbit satisfying mission constraints and minimizing propellant expenditure. In the case of sub-GTO, the optimal strategy is to first perform an in-plane maneuver at perigee to raise the apogee to synchronous level and then perform combined maneuvers at the synchronous apogee to achieve the desired drift orbit. The perigee burn opportunities were examined considering ground station visibility requirement for monitoring the burn. Two maneuver strategies were proposed: an optimal five-burn strategy with two perigee burns centered around perigee#5 and perigee#8 with partial ground station visibility and three apogee burns with dual station visibility, a near-optimal five-burn strategy with two off-perigee burns at perigee#5 and perigee#8 with single ground station visibility and three apogee burns with dual station visibility. The range vector profiles were studied in the s/c frame during LAM burn phases and accurate polarization predictions were provided to the supporting ground stations. The near optimal strategy was selected for implementation in order to ensure full visibility during each LAM burn. Contingency maneuver plans were generated in preparation for specified Propulsion system related contingencies. Maneuver plans were generated considering 3-sigma dispersions in T.O. GSAT-12 was launched in July, 2011 and positioned at 83 deg East longitude. The estimated operational life is about 11 years which was realized through the operationally optimal maneuver strategy selected from the detailed mission analysis.

1.0 Introduction

GSAT-12 is a communication satellite buit by ISRO, weighs about 1410 kg at lift-off. GSAT-12 is configured to carry 12 extended C-band transponders to meet the country's growing demand for transponders in a short turnaround time.

GSAT-12 was launched into a sub-Geosynchronous Transfer Orbit (sub GTO) by PSLV with a 284 km perigee and 21,000 km apogee with an inclination of 18 deg with respect to the equatorial plane. After injection into this preliminary orbit, solar panels were automatically deployed. The Digital Sun Sensor (DSS) is mounted along Roll axis and gyro calibration is performed in Roll-Sun-Pointing orientation. The Liquid Apogee Motor (LAM), which is mounted along –Yaw axis, is used for placing the s/c in the desired Geostationary orbit. In LAM burn phase, the s/c West face (-Roll) will be towards the Earth for communication. After this, the deployment of the antenna and the three axis stabilization of the satellite are performed. GSAT-12 is positioned at 83 deg East longitude and co-located with INSAT-2E and INSAT-4A satellites. The 12 extended C-band transponders of GSAT-12 will augment the capicity in the INSAT system for various communcation services like Tele-education, Telemedicine and for Village Resource Centres (VRC).

PSLV was the identified launcher for GSAT-12. In the early part of the mission analysis, the dry mass of the s/c was given as 579 kg. It was found that if PSLV targets to a standard GTO with synchronous apogee, we do not meet the constraint of having minimum 7 years of operational life with the total s/c mass delivered in T.O. PSLV came up with different proposals of injecting higher s/c masses into sub-geosynchronous T.O. (sub-GTO) which would allow us to load more propellant in the s/c. GSAT-12 is equipped with a unified bi-propellant propulsion system for orbit raising and

AOCS requirements. There are two 390 litre propellant tanks in the s/c with maximum possible loading of over 850 kg. The delta-V and propellant requirements, to achieve desired target GEO orbit, for three sub-GTO cases proposed by PSLV are shown in Table-1. The optimal maneuver strategy, of first performing an in-plane velocity increase maneuver at perigee to raise the sub-synchronous apogee to synchronous level followed by combined apogee maneuvers to raise perigee and also reduce inclination to acquire the desired GEO orbit, was considered in this study. Case-3 was selected which gives us additional 2 years life compared to Case-1. The finalized GSAT-12/PSLV-C-17 transfer orbit parameters at injection are provided in Table-2 respectively.

Table-1: PSLV Sub-GTO Cases

Sub-GTO PRG x APG (km)	S/C mass (kg) at Lift-off	Prop. Loading (kg)	Total Impv. ΔV (m/s)	Total Δm (kg)	Rem. Prop. (kg)
249 x 22875	1331	752	1895.0	610.3	141.7
244 x 21901	1373	794	1926.7	637.2	156.8
244 x 20911	1411	832	1960.5	663.0	169.0

Table-2: GSAT-12/PSLV-C-17 Injection Parameters

- S/c mass at lift-off : 1410.6 kg
- Dry mass : 561.6 kg, Propellant mass : 849 kg

Orbital Parameters at Injection	
Epoch (U T)	2011-07-06, 11:37
Perigee Height	284.170 km
Apogee Height	21009.990 km
Inclination	17.966 deg
Arg. of Perigee	177.945 deg
RAAN	43.259 deg
Mean Anomaly	4.732 deg
Orbit Period	6.1 hr

2.0 Launch Window

GSAT-12 is equipped with two earth sensors (ES), mounted at 6.1 deg from Yaw axis in Yaw-Pitch plane, with a scanning FOV of 45 deg. ES provides roll and pitch attitude information. The Earth sensor scan geometry is shown in Fig.1. α is the maximum half chord width, β is the angle between scan center direction and chord center direction, γ is the mounting angle and ξ is the half chord width. The digital sun sensor (DSS) is mounted along Roll axis and provides yaw and pitch information. There are three gyroscopes which are used for attitude reference during the liquid engine (LAM) firing operations. The GSAT-12 Launch window was generated considering the following constraints:

- The earth sensor visibility duration, as the s/c moves in T.O. in Roll-Sun-Pointing mode, should be at least 60 minutes. This is required for T.O. earth acquisition operation and calibration of the gyros, before LAM firing, using the ES Roll and DSS Yaw and Pitch data
- Eclipse duration should not exceed 35 min in T.O.

Figure-1: Earth Sensor Scan geometry

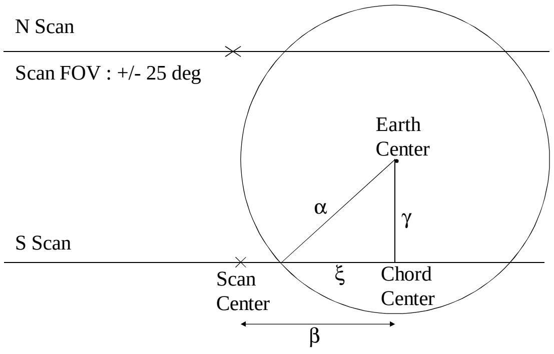
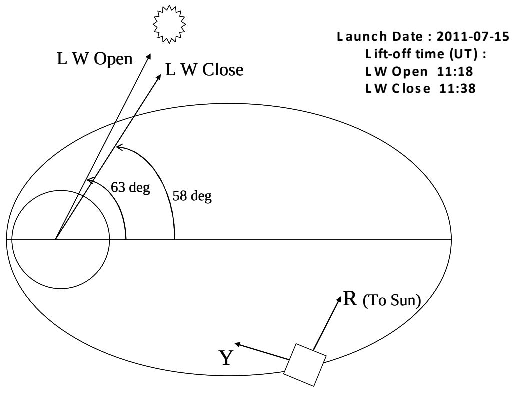


Figure-2: Sun-Orbit geometry and spacecraft orientation for gyro-cal.

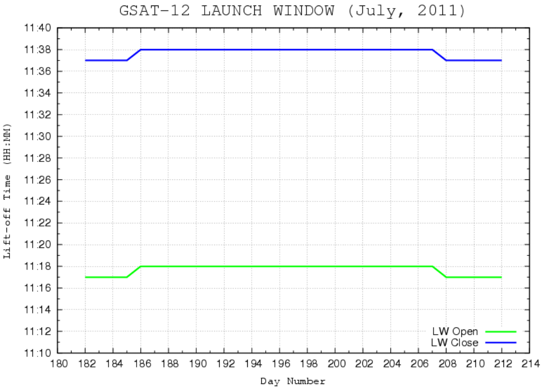


The Sun-Orbit geometry and the spacecraft orientation for gyro-cal. are shown in Fig-2. As the s/c moves in T.O. with Roll to sun and Yaw towards earth in the sun-satellite-earth plane, earth will come into the ES FOV in the region around the time when earth-satellite-sun are orthogonal. Due to the smaller orbit size, the ES visibility duration in is also small and appropriate pitch bias is required to extend the ES visibility. Earth Sensor (ES) scale factor varies as a function of altitude. The altitude profile was provided to sensors team to work out the scale factors. The ES visibility summary for each Maneuver orbit, where LAM firing is planned, is shown in Table 3 for launch window open case. The launch window open and close times in terms of lift-off time, for July, 2011 are shown in Fig.-3.

Table-3: ES Visibility Summary

Orbit No.	Phase	Pitch Bias (deg)	Duration (min)
4	Pre-MVR#1 at PRG#5	0	45
		-10	58
		-20	66
7	Pre-MVR#2 at PRG#8	0	67
		-10	89
		-20	100
9	Pre-MVR#3 at APG#9	10	106
		0	159
11	Pre-MVR#4 at APG#11	10	131
		0	154
12	Pre-MVR#5 at APG#12	10	141
		0	142

Figure-3: GSAT-12 Launch Window



3.0 Transfer Orbit Events

The ground station network comprised Hassan which is the Control Center, Biak in Indonesia which is also an ISRO station and three external stations - Kumsan in South Korea, Fillmore in US and Fucino in Italy. The s/c is in eclipse for about 25 min after injection. In each of the later T.O.'s the s/c will be in eclipse for about 32 min around perigee.

The T.O. visibility for nine revolutions is graphically shown in Fig-4. There is visibility for Biak for over 5 min from injection. Fillmore acquires the s/c about 30 min after injection, considering 5 deg elevation, and supports T.O.-1. For the selected operationally optimal 5-burn strategy, the details of which are described in the subsequent Maneuver Strategy section, the first Perigee burn opportunities were found to be near Perigee#5 and Perigee#9 where Biak and Hassan visibilities exist. Perigee#5 is the nominal first LAM burn opportunity and Perigee#9 is the backup opportunity.

The elevation profiles for all the ground stations for the first four T.O.'s are shown in Fig-5 and those for T.O.-5 to T.O.-8 are shown in Fig. 6.

Figure-4: T.O. Visibility chart

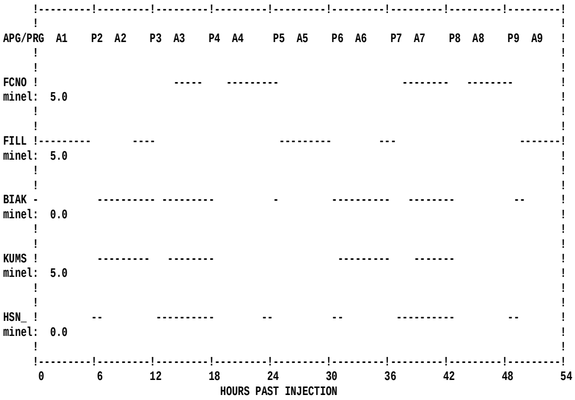


Figure-5: Elevation Profiles (T.O.1,2,3,4)

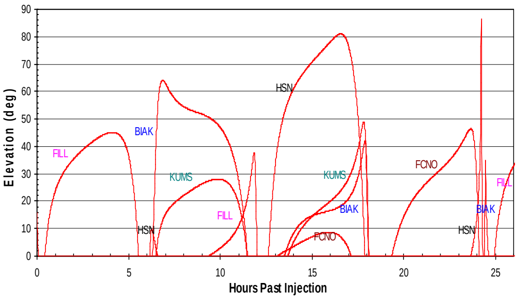
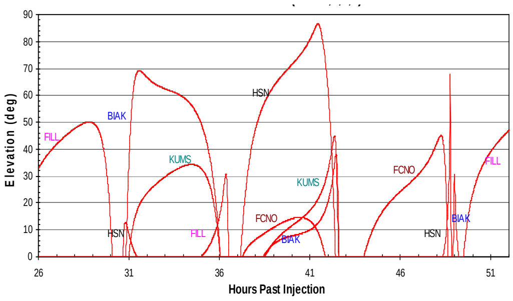


Figure-6: Elevation Profiles (T.O.5,6,7,8)



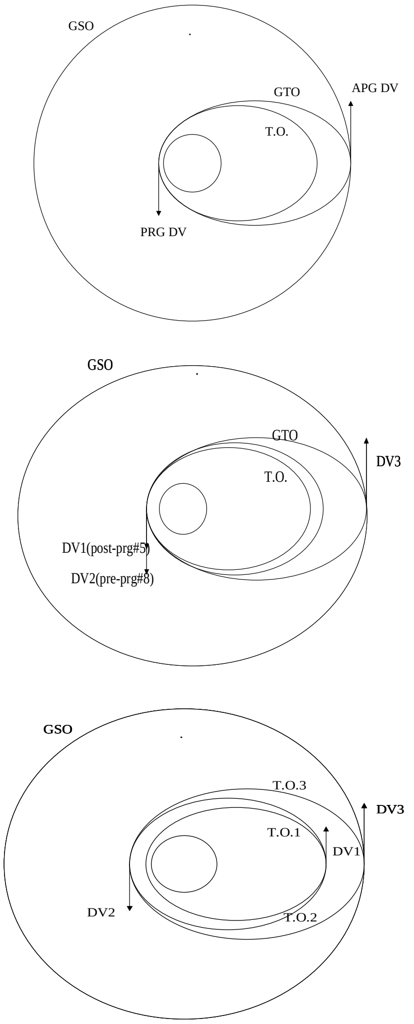
4.0 Maneuver Strategies

The objective of the maneuver strategy is to achieve the desired drift orbit satisfying the mission constraints and minimizing the propellant expenditure. Since the T.O. apogee is at a sub-synchronous altitude of 21000 km, the optimal strategy is to first perform an in-plane maneuver at perigee to raise the T.O. apogee to synchronous level and then perform combined maneuvers at the synchronous apogee to achieve the desired drift orbit. The perigee burn opportunities were examined considering ground station visibility requirement for monitoring the burn.

The following maneuver strategies are proposed (depicted in Fig. 7)

- Optimal 5-Burn Strategy : Two perigee burns centered around perigee#5 and perigee#8 with partial ground station visibility and three apogee burns with dual station visibility
- Operationally Optimal 5-Burn Strategy : Two off-perigee burn at perigee#5 and perigee#8 with single ground station visibility and three apogee burns with dual station visibility
- Sub-Optimal 6-Burn Strategy: Six-burn strategy fully satisfying visibility constraints
    - First burn at Apogee-2 to raise perigee to 1700 km altitude, along with appropriate inclination reduction, so that we obtain sufficient visibility for network G/S for the perigee maneuver at perigee#5
    - Next two burns as in-plane maneuvers at perigee#5 and perigee#8 to raise T.O. apogee to synchronous level
    - Three more apogee burns to achieve the desired drift orbit

Figure-7: Depiction of maneuver strategies



4.1 Optimal 5-Burn Maneuver Strategy

The optimal Strategy is summarized in Table 4. The first two of five burns are planned as in-plane maneuvers centered on Perigee#5 and Perigee#8 to raise the T.O. apogee to synchronous level. The total delta-v imparted in the perigee burns is about 363 m/s and the propellant consumed is 156.7 kg. The total perigee burn duration is about 1088 sec.

Three more burns are planned at apogees 9, 11 and 12 respectively to achieve the desired drift orbit. The time taken for drift orbit acquisition is nearly 5 days from launch. The total delta-v for achieving desired GSO is about 1991.3 m/s and the corresponding propellant requirement is about 667.7 kg.

The problem in implementing this optimal strategy is that there is partial visibility during the perigee burns. The last 4 minutes of the first burn can be monitored from Biak. Mission requires full visibility of all LAM burns because of the criticality of the operation.

Table-4: Optimal 5-burn Maneuver Strategy

S/C Mass	Lam Thrust	Lam Isp
1409.704 kg	438.500 N	318.300 sec

MVR No.	APG/ PRG No.	Burn %	Delta-V (m/s)	Burn Start Time (UT)	Burn Dur. (sec)	Prop. (kg)
1	PRG-5	-	176.5	2011-7-16,11:58	545.0	78.5
2	PRG-8	-	186.6	2011-7-17,11:16	542.9	78.2
3	APG-9	37.5	608.6	2011-7-18,02:52	1571.4	223.2
4	APG-11	57.6	935.1	2011-7-19,04:20	1902.0	267.2
5	APG-12	4.9	79.5	2011-7-20,02:47	136.9	19.2
TOTALS			1986.3		4698.2	666.3

ORBITAL CHARACTERISTICS							
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE MVR1	285.0	21015.2	17.98	51.6	95.9	267.61	6.143
POST MVR1	284.9	26877.7	17.98	51.6	137.1	242.75	7.795
POST MVR2	285.5	35949.9	17.98	51.1	147.4	200.59	10.599
POST MVR3	6911.3	35786.6	8.30	50.5	68.2	168.03	12.763
POST MVR4	31650.7	35783.4	0.34	38.9	45.1	26.17	22.195
POST MVR5	35522.8	35783.3	0.15	260.0	71.4	1.70	23.821

4.2 Operationally Optimal 5-Burn Nominal Maneuver Strategy

The operationally optimal nominal maneuver strategy, which was implemented for GSAT-12, is summarized in Table 5. The first two of five burns are in-plane maneuvers carried out post-perigee#5 and pre-perigee#8, to raise the T.O.

apogee to synchronous level. The skewing of the burns is done to achieve visibility during the burn for monitoring. The delta-V imparted in the perigee burns is about 375.2 m/s which is nearly 12 m/s higher than in the optimal strategy. The propellant consumed is about 161.7 kg which is about 5 kg more than optimal. The burn duration is about 1122 sec. These burns are planned in inertially held mode. The latch valve gas side (LVG) is normally opened about five minutes before the first LAM burn start to allow the Helium gas to flow into the propellant tanks and the pressure regulator system maintains the tank pressure at the set operating value. In case of GSAT-12, the LVG open operation was advanced by over 3 hours before Apogee-4 to be ready for an immediate contingency burn if the pressure regulation fails.

Table-5: Operationally Optimal 5-Burn Maneuver Strategy

MVR No.	APG/ PRG No.	Burn %	Delta-V (m/s)	Burn Start Time (UT)		Burn Dur. (sec)	Prop. (kg)
1	POST-PRG#5	-	130.6	2011-7-16,12:04		406.0	58.5
2	PRE-PRG#8	-	244.6	2011-7-17,09:36		716.0	103.2
3	APG#9	45.2	732.4	2011-7-18,01:26		1847.6	262.3
4	APG#11	49.8	806.7	2011-7-19,04:23		1602.6	225.1
5	APG#12	5.0	81.0	2011-7-20,02:46		139.1	19.5
TOTALS			1995.3			4711.3	668.6
ORBITAL CHARACTERISTICS							
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE MVR1	284.6	21029.2	17.98	51.6	123.3	267.55	6.146
POST MVR1	294.8	25069	17.98	51.6	152.5	250.59	7.274
POST MVR2	321.0	35968.9	17.98	51.1	148.2	200.32	10.616
POST MVR3	8913.3	35783.3	6.89	50.4	89.0	157.55	13.46
POST MVR4	31587.1	35781.5	0.36	39.2	45	26.58	22.167
POST MVR5	35524.8	35781.4	0.15	260.0	71.7	1.7	23.821

The elevation profile around perigee#5 is shown in Fig. 8. The spacecraft orientation for maneuver-1 is depicted in Fig. 9. The maneuver is in eclipse region. Before eclipse entry, only CASS AEV output is available for orientation verification. The effect of maneuver errors in MVR-1 was analyzed.

The elevation profile around perigee#8 is shown in Fig. 10. The spacecraft orientation for maneuver-2 is depicted in Fig. 11. The maneuver is in sun lit region and eclipse starts just after burn end. For orientation verification, SPSS and CASS AEV outputs are available assuming that the panel normal is along AEV.

Figure-8: Elevation Profile around perigee#5 (MVR#1)

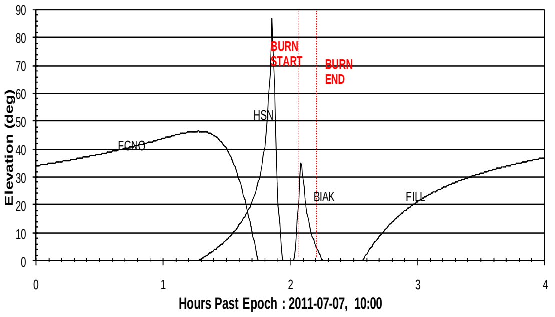


Figure-9: Post-PRG#5 Spacecraft Orientation (MVR#1)

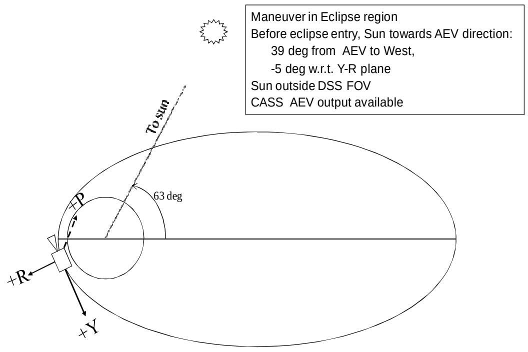
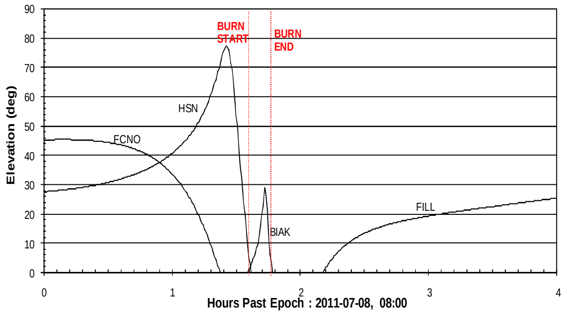

Maneuver in Eclipse region
Before eclipse entry, Sun towards AEV direction:
39 deg from AEV to West,
-5 deg w.r.t. Y-R plane
Sun outside DSS FOV
CASS AEV output available
To sun
63 deg
+P
+R
+Y

Figure-10: Elevation Profile around perigee#8 (MVR#2)



Three more burns are planned at apogees 9, 11 and 12 respectively to achieve the desired drift orbit. The spacecraft orientation for maneuver-3 is depicted in Fig. 12. For orientation verification, SPSS and CASS R/Y East outputs are available assuming that the panel normal is along AEV. The time taken for drift orbit acquisition is nearly 5 days from launch. After the final maneuver (MVR-5), the s/c is at 71.7 deg East longitude with a drift rate of 1.7 deg/rev. The total delta-v for achieving desired GSO is 2000.3 m/s and the corresponding propellant requirement is about 670 kg. The drift orbit inclination achieved is 0.15 deg with optimal ascending node of 260 deg. With this, the s/c will enter NSSK window 22 days after MVR-5 and the first NSSK will be due another 100 days later.

Figure-11: Pre-PRG#8 Spacecraft Orientation (MVR#2)

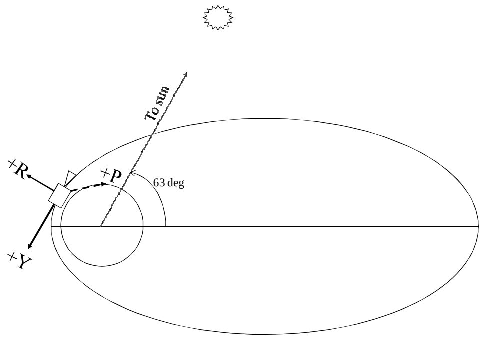
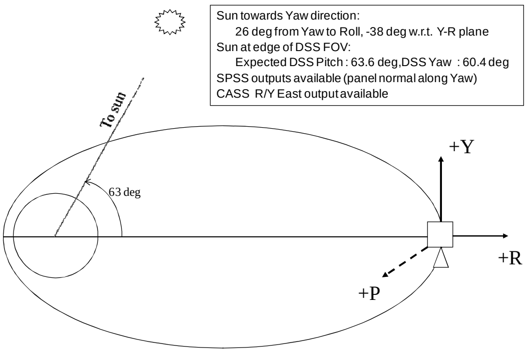


Figure-12: Apogee Maneuver Orientation (APG#9)


Sun towards Yaw direction:
26 deg from Yaw to Roll, -38 deg w.r.t. Y-R plane
Sun at edge of DSS FOV:
Expected DSS Pitch : 63.6 deg,DSS Yaw : 60.4 deg
SPSS outputs available (panel normal along Yaw)
CASS R/Y East output available
To sun
63 deg
+Y
+R
+P

4.3 Contingency Maneuver Plans

Maneuver plans were worked out in readiness for following contingency scenarios:

- A near full burn at Apogee-1 in case of a leak in the propulsion system observed after separation from PSLV
- A large first burn around Apogee-4 in case of pressure regulator failure contingency after Latch Valve Gas side (LVG) is opened before apogee#4, which is over three hours before the first post-perigee#5 LAM burn
- Plan for completing LAM burns within another 14 hours, if a leak is observed in the propulsion system before the end of MVR-1

4.3.1 Contingency Maneuver at Apogee-1

In case of a propulsion contingency, a near full burn may have to be carried out at apogee-1. The s/c is visible only to Fillmore in T.O.-1. The longitude at apogee-1 is about 217 deg East. The GEO slot of 83 deg East is 226 deg east of the apogee-1 longitude.

An 86.0 % burn is planned which results in a longitude drift rate of about 91 deg/rev so that the s/c will be at about 34 deg East one and half revolutions later. The plan is summarized in Table-6. This strategy accounts for a 2% error in LAM thrust and 1 deg error in thrust declination.

It is assumed that LAM is not usable for the second burn. The second burn can be carried out using the four AY thrusters in backup LAM mode. The deltav imparted in the second burn is about 383 m/s. The AY firing duration is about 3275 sec and the propellant consumed is 95.4 kg. The total deltav for achieving GSO is 2425 m/s and the corresponding total fuel is nearly 777.6 kg. The penalty in deltav and propellant consumed with respect to nominal plan is 425 m/s and 107.6 kg respectively.

Table-6: Contingency Maneuver at Apogee-1

AY Thrust	AY Isp
168.0 N	280.0 sec sec

<table>
<tr><th>LAM/ AY</th><th>APG No.</th><th colspan="2">Delta-V (m/s)</th><th colspan="3">Burn Duration (sec)</th><th>Prop. (kg)</th></tr>
<tr><td>LAM</td><td>1</td><td colspan="2">2024.6</td><td colspan="3">4736.5</td><td>677.2</td></tr>
<tr><td>AY</td><td>3</td><td colspan="2">383.0</td><td colspan="3">3274.0</td><td>95.4</td></tr>
<tr><td colspan="2">TOTALS</td><td colspan="2">2407.6</td><td colspan="3"></td><td>772.6</td></tr>
<tr><td colspan="8">ORBITAL CHARACTERISTICS</td></tr>
<tr><td></td><td>PRG. ALT.</td><td>APG. ALT.</td><td>INCL. (deg)</td><td>RAAN (deg)</td><td>Long (deg)</td><td>Long. Drift (deg/rev)</td><td>Period (hrs)</td></tr>
<tr><td>PRE AMF1</td><td>288.3</td><td>20936.6</td><td>17.97</td><td>52.3</td><td>256.3</td><td>267.91</td><td>6.122</td></tr>
<tr><td>POST AMF1</td><td>20925.5</td><td>35786.3</td><td>3.35</td><td>56.9</td><td>267.9</td><td>90.83</td><td>17.895</td></tr>
<tr><td>PRE AMF2</td><td>20928.0</td><td>35779.2</td><td>3.35</td><td>56.9</td><td>34.0</td><td>90.86</td><td>17.894</td></tr>
<tr><td>POST AMF2</td><td>34905.9</td><td>35717.2</td><td>0.15</td><td>260.0</td><td>34.0</td><td>6.06</td><td>23.532</td></tr>
</table>

4.3.2 Contingency Maneuver at Apogee-4

A large first burn is required in case of a propulsion contingency after Latch Valve Gas side (LVG) open before apogee#4. The strategy with MVR-1 at apogee-4 is summarized in Table-7. The deltav imparted in the first burn is about 1541 m/s and the propellant consumed is 553.2 kg. The burn duration is about 3869.4 sec. The post-MVR#1 drift rate is about 183 deg/rev. Second burn is planned at apogee-7, through this maneuver perigee will be corrected fully to the synchronous height. The post-MVR#2 drift rate is about 90.8 deg/rev. Remaining correction is planned at Apogee-10 and Apogee-11. The total deltav for achieving GSO is about 2405 m/s and the corresponding total propellant is nearly 762 kg. The penalty in deltav and propellant consumed with respect to nominal plan is 405 m/s and 92 kg respectively.

Table-7: Contingency Maneuver at Apogee-4

MVR No.	APG No.	Delta-V (m/s)		Burn Start Time (UT)		Burn Dur. (sec)	Prop. (kg)
1	4	1541		2011-7-16,08:24		3869.4	553.2
2	7	476.1		2011-7-17,20:19		854.8	122.2
3	10	269.2		2011-7-19,17:19		428.2	61.2
4	11	113.8		2011-7-20,15:01		171.7	24.1
TOTALS		1995.3				4711.3	668.6
ORBITAL CHARACTERISTICS							
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE MVR1	288.8	20935.3	17.97	51.7	340.8	267.92	6.122
POST MVR1	18900.7	20933.2	4.58	53.9	348.8	182.70	11.787
POST MVR2	20929.2	35789.1	3.07	54.0	173.6	90.80	17.898
POST MVR3	30363.2	35767.6	0.74	50.2	37.2	34.27	21.656
POST MVR4	35545.8	35760.9	0.15	260.0	71.5	1.70	23.822

Table-8: Contingency Maneuver at Apogee-6

MVR No.	APG/ PRG No.	Delta-V (m/s)		Burn Duration (sec)			Prop. (kg)
1	POST-PRG#5	130.8		410.0			58.3
2	APG-6	1899.7		4359.3			620.3
3*	APG-10	259.3		2270.0			66.2
TOTALS		2289.8					744.8
ORBITAL CHARACTERISTICS							
	PRG. ALT.	APG. ALT.	INCL. (deg)	RAAN (deg)	Long (deg)	Long. Drift (deg/rev)	Period (hrs)
PRE AMF1	283.2	21019.5	17.97	42.5	123.3	267.6	6.143
POST AMF1	293.5	25064.9	17.97	42.5	152.8	250.61	7.273
PRE AMF2	296.4	24988.6	17.96	42.2	135	250.93	7.252
POST AMF2	24982.7	35790.5	1.98	37.4	139.5	66.89	19.487

4.3.2 Contingency Maneuver at Apogee-6

If a leak is observed in the propulsion system before the end of MVR-1, then LAM burn has to be completed within 14 hours. This plan is summarized in Table-8. The second LAM burn is planned at apogee#6. Subsequently, two maneuvers are planned at apogee#10 and apogee#11 using AY 7hrusters in backup plan mode to impart 259 m/s delta-v. The total deltav for achieving GSO is about 2295 m/s and the corresponding total propellant is nearly 746.5 kg. The penalty in deltav and propellant consumed with respect to nominal plan is about 295 m/s and 76.5 kg respectively.

4.4 Propellant Saving Due to Thrust Vector Steering Mode of Maneuver Operation

A study was made to assess the saving in propellant obtainable due to carrying out the orbit maneuver with thrust vector steering as compared to maneuver with inertially held thrust direction. Simulations were carried out of the following finite burn cases

- MVR-1 at Perigee#5 of Nominal strategy
- MVR-2 at Perigee#8 of Nominal strategy
- Contingency single LAM burn at Apogee-1

The results of the study are provided in Table 8. There is a total gain about 1.6 kg in the case of Perigee burns of nominal 5-burn strategy due to performing the burn with steering. For the case of contingency single LAM burn at Apogee-1, there is saving of over 5 kg due to the large burn duration of over 78 min.

Table-9: Comparison b/w Maneuver Strategies

Strategy	Thrust Vector (MVR Type)	Δv (m/s)	Δm (kg)	Saving in	
				Δv (m/s)	Δm (kg)
MVR#1	Inertially Held Steering	130.79 130.13	58.34 58.05	-- 0.65	-- 0.28
MVR#2	Inertially Held Steering	246.05 242.91	103.30 102.04	-- 3.14	-- 1.27
Cont. Burn at APG#1	Inertially Held Steering	2022.84 2002.07	676.84 671.89	-- 20.77	-- 4.95

4.5 Maneuver Strategies for 3-Sigma Low T.O.

The 3-sigma low T.O. is constructed with lower apogee, perigee and higher inclination values by the specified dispersion and with higher separation between apside and node. Considering Maneuver region visibilities, both near-optimal and sub-optimal strategies are worked out. The 3-sigma dispersions in the GTO parameters as provided by PSLV are as follows:

Table-10: PSLV 3-sigma Dispersions

Dispersions	
Perigee height (km)	± 5
Apogee Height (km)	± 675
Inclination (deg)	± 0.2
Argument of Perigee (deg)	± 0.2

4.5.1 Operationally-optimal Maneuver Strategy for 3-Sigma Low T.O.

The operationally optimal 6-burn Strategy for 3-sigma low T.O. is summarized in Table 11. The total perigee burn is splits into three steps. The three perigee burns are planned as in-plane off-perigee maneuvers at Perigee#5, Perigee#9 and Perigee#12 to raise the T.O. apogee to synchronous level. The delta-v imparted in the perigee burns is 400.6 m/s and the propellant consumed is about 172 kg. The total perigee burn duration is about 1193 sec.

Three more burns are planned at apogees 15, 17 and 19 respectively to achieve the desired drift orbit. The time taken for drift orbit acquisition is nearly 8.5 days from launch. The total delta-v for achieving desired NGSO is about 2033 m/s and the corresponding propellant requirement is about 677.5 kg. The penalty in delta-v, as compared to the nominal strategy of expected nominal T.O. case, is about 33 m/s and that in propellant is about 7.5 kg.

Table-11: Operationally-optimal Maneuver Strategy for 3-Sigma Low T.O.

<table>
<tr><th>MVR No.</th><th>APG/ PRG No.</th><th>Burn %</th><th>Delta-V (m/s)</th><th colspan="2">Burn Start Time (UT)</th><th>Burn Dur. (sec)</th><th>Prop. (kg)</th></tr>
<tr><td>1</td><td>POST-PRG#5</td><td>-</td><td>82.0</td><td colspan="2">2011-7-16,11:19</td><td>257.0</td><td>37.0</td></tr>
<tr><td>2</td><td>PRE-PRG#9</td><td>-</td><td>215.6</td><td colspan="2">2011-7-17,13:28</td><td>644.0</td><td>92.8</td></tr>
<tr><td>3</td><td>POST-PRG#12</td><td>-</td><td>103.0</td><td colspan="2">2011-7-18,16:28</td><td>292.0</td><td>42.1</td></tr>
<tr><td>4</td><td>APG#15</td><td>34.1</td><td>554.8</td><td colspan="2">2011-7-20,04:58</td><td>1426.9</td><td>202.6</td></tr>
<tr><td>5</td><td>APG#17</td><td>60.9</td><td>991.1</td><td colspan="2">2011-7-21,05:53</td><td>2008.9</td><td>282.2</td></tr>
<tr><td>6</td><td>APG#19</td><td>5.0</td><td>81.3</td><td colspan="2">2011-7-23,02:29</td><td>138.2</td><td>19.4</td></tr>
<tr><td colspan="3">TOTALS</td><td>2027.8</td><td colspan="2"></td><td>4767.1</td><td>676.1</td></tr>
<tr><td colspan="8">ORBITAL CHARACTERISTICS</td></tr>
<tr><td></td><td>PRG. ALT.</td><td>APG. ALT.</td><td>INCL. (deg)</td><td>RAAN (deg)</td><td>Long (deg)</td><td>Long. Drift (deg/rev)</td><td>Period (hrs)</td></tr>
<tr><td>PRE MVR1</td><td>279.5</td><td>20354.6</td><td>18.18</td><td>51.8</td><td>125.4</td><td>270.3</td><td>5.963</td></tr>
<tr><td>POST MVR1</td><td>280.6</td><td>22746.4</td><td>18.18</td><td>51.8</td><td>144.8</td><td>260.49</td><td>6.616</td></tr>
<tr><td>POST MVR2</td><td>310.2</td><td>30675.8</td><td>18.18</td><td>51.0</td><td>83.4</td><td>225.51</td><td>8.942</td></tr>
<tr><td>POST MVR3</td><td>327.1</td><td>35904.4</td><td>18.18</td><td>50.5</td><td>90.8</td><td>200.61</td><td>10.597</td></tr>
<tr><td>POST MVR4</td><td>6156.0</td><td>35788.4</td><td>9.09</td><td>49.7</td><td>34.0</td><td>171.93</td><td>12.504</td></tr>
<tr><td>POST MVR5</td><td>31594.5</td><td>35767.2</td><td>0.36</td><td>38.3</td><td>18.7</td><td>26.62</td><td>22.165</td></tr>
<tr><td>POST MVR6</td><td>35539.9</td><td>35766.1</td><td>0.15</td><td>260.0</td><td>72.1</td><td>1.70</td><td>23.821</td></tr>
</table>

5.0 Maneuver Realisation

Based on the carried out detailed mission analysis the 5-burn operationally optimal maneuver strategy was implemented for the orbit raising of GSAT-12. The launch dispersions were well within the quoted dispersions from PSLV. A comparison of maneuver planned and realized in terms of delta-V and Thrust are shown in Table 12 & Table 13.

Table-12: Realized delta-V and burn durartion

MVR No.	PRG/APG No.	Burn %	Burn Dur. (sec)	Delta-V (m/s)		
				Expected	Realized	Diff.
1	PRG-5	-	414.0	128.05	122.85	-5.20
2	PRG-8	-	801.2	256.84	256.28	-0.56
3	APG-9	56.3	2008.0	773.60	800.36	26.76
4	APG-11	38.9	1388.5	710.21	725.83	15.62
5	APG-12	4.8	168.6	96.38	97.70	1.32
Totals			4780.3		2003.02	

Table-13: Realized Thrust

MVR No.	PRG/APG No.	Thrust (N)			Roll Error (deg)
		Expected	Realized	Diff.	
1	PRG-5	421.4	404.4	-17	-
2	PRG-8	412	411.13	-0.87	-
3	APG-9	421	433.85	12.85	-0.2
4	APG-11	433.85	442.4	8.55	0.06
5	APG-12	422	427.75	5.75	0

6.0 Conclusion

The GSAT-12 mission successfully accomplished combined optimization of launch vehicle and satellite capabilities to maximize the operational life of the s/c. The estimated operational life is about 11 years which was realized through the operationally optimal maneuver strategy selected from the detailed mission analysis. The accurate polarization predictions were provided during all the phases of the mission for the ground station antenna polarization settings.

References:

1. “Mission Analysis for GSAT-12”, Dr. Kuldeep Negi, Satyendra Kumar Singh, K N Srinivasamurthy, B S Kiran, FDG/ISAC, July 2011
2. V.A. Chobotov, “Orbital Mechanics” Third Edison
3. Roger R Bate, Donald D. Mueller, and Jerry E White, “Fundamentals of Astrodynamics”, New York Dover Publications

4. Pocha, J.J, 1987, “An Introduction to Mission Design for Geostationary Satellites”, Boston: D.Reidel Publishing Company
5. Wertz, James R., ed. 1978, “Spacecraft Attitude Determination and Control” Holland:D. Reidel Publishing Company